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14. ABSTRACT
This project has been concerned with joint transmitter-receiver adaptation in a distributed, peer-to-peer wireless network. Parameters that can be adapted at the transmitter include rate, power, and signatures in space-time-frequency. In this report we summarize our work on the following topics: (1) Limited feedback schemes for optimizing spatial signatures for Multi-Input Multi-Output (MIMO) channels, and power and rates for multi-carrier transmission; (2) Optimization of training overhead for MIMO block fading channels with least squares filter estimation; (3) Optimization of training overhead with limited feedback for wideband multi-carrier channels, and for a narrowband channel with beamforming; (4) Allocation of training and data power U

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Final Report: Adaptive Transceivers for Wireless Spread Spectrum Networks

ABSTRACT

This project has been concerned with joint transmitter-receiver adaptation in a distributed, peer-to-peer wireless network. Parameters that can be adapted at the transmitter include rate, power, and signatures in space-time-frequency. In this report we summarize our work on the following topics: (1) Limited feedback schemes for optimizing spatial signatures for Multi-Input Multi-Output (MIMO) channels, and power and rates for multi-carrier transmission; (2) Optimization of training overhead for MIMO block fading channels with least squares filter estimation; (3) Optimization of training overhead with limited feedback for wideband multi-carrier channels, and for a narrowband channel with beamforming; (4) Allocation of training and data power for a time-selective fading channel with known channel state information; (5) Source-channel coding schemes for block fading channels based on erasure and multi-resolution coding; and (6) Distributed power control for peer-to-peer networks based on the exchange of interference prices. Our main results characterize what channel state information should be exchanged between the receiver and transmitter (or neighboring transmitters in a distributed network) to provide substantial gains in spectral efficiency.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Y. Sun and M. L. Honig, "Performance of Reduced-Rank Equalization", IEEE Transactions on Information Theory, Oct. 2006

Y. Sun and M. L. Honig, "Reduced-Rank Signature-Receiver Adaptation", IEEE Transactions on Wireless Communications, Oct. 2006.

M. Peacock, I. Collings, and M. L. Honig, "Unified Large System Analysis of MMSE and Adaptive Least Squares Receivers for a class of Random Matrix Channels", IEEE Transactions on Information Theory, Vol. 52, No. 8, pp. 3567-3600, August 2006.

J. Huang, R. Berry, and M. L. Honig,
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Vol. 24, No. 5, May 2006.

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``Asymptotic Analysis of LMMSE Multiuser Receivers for Multi-Code Multi-Carrier CDMA in Rayleigh Fading",
IEEE Transactions on Communications, July 2004.

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M. Agarwal, D. Guo, and M. L. Honig,
"Error Exponent for Gaussian Channels with Partial Sequential Feedback",
IEEE Int. Symposium on Information Theory, Nice, France, July 2007.

W. Santipach and M. L. Honig,
"Optimization of Training and Feedback for Beamforming over a MIMO Channel",
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Proc. 2004 Int. Symposium on Spread Spectrum Systems and Applications, Sydney, Australia, Sept. 2004.

Y. Sun and M. L. Honig, "Reduced-Rank Signature and Receiver Adaptation for CDMA", IEEE Military Communications Conference,
Monterey, Ca., October 2004.

K. Zachariadis, M. L. Honig, and A. K. Katsaggelos, "Source Fidelity Over a Multi-hop Fading Channel", IEEE Military Communications
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"On Isometric Multi-user MC-CDMA in Frequency-Selective Fading",
Proc. IEEE Int. Symposium on Information Theory,
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"Asymptotic Capacity of Beamforming with Limited Feedback",
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M. J. M. Peacock, I. B. Collings, and M. L. Honig,
"Analysis of Multiuser Peer-to-Peer MC-CDMA with Limited Feedback",
Proceedings IEEE International Conference on Communications,
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MC-CDMA Systems in Frequency-Selective Rayleigh Fading",
Proc. IEEE International Conference on Communications,
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Y. Sun and M. L. Honig,
"Minimum Feedback Rates for Multi-Carrier Transmission With Correlated Frequency-Selective Fading",
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H. Bi and M. L. Honig,
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IEEE Globecom Conf., San Francisco, Ca., December 2003.

M. Peacock, I. Collings, and M. L. Honig,
"General Asymptotic LMMSE SINR and Spectral Efficiency for Multi-user Multi-signature MC-CDMA in Multipath Rayleigh Fading",
IEEE Globecom Conf, San Francisco, Ca., December 2003.

W. Santipach and M. L. Honig,
"Asymptotic Performance of MIMO Wireless Channels with Limited Feedback",
Proc. 2003 Milcom Conf., Boston, Mass., Oct. 2003.

W. Santipach, Y. Sun, and M. Honig,
"Benefits of Limited Feedback for Wireless Channels",
Proc. 2003 Allerton Conf., Monticello, IL, Oct. 2003.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 26

(d) Manuscripts

Y. Sun and M. L. Honig, "Asymptotic Capacity of Multi-Carrier Transmission with Frequency-Selective Fading and Limited Feedback", submitted to IEEE Transactions on Information Theory.

D. J. Ryan, I. V. L. Clarkson, I. B. Collings, D. Guo, and M. L. Honig, "QAM and PSK Codebooks for Limited Feedback MIMO Beamforming", submitted to IEEE Transactions on Communications.

W. Santipach and M. L. Honig, "Capacity of a Multi-Input/Multi-Output Channel with a Quantized Precoding Matrix", submitted to IEEE Transactions on Information Theory.

M. Peacock, I. B. Collings, and M. L. Honig, "Eigenvalue Distributions of Sums and Products of Large Random Matrices via Incremental Expansions", submitted to IEEE Transactions on Information Theory.

K. Zachariadis, M. L. Honig, and A. Katsaggelos, "Source Fidelity Over Fading Channels: Performance of Erasure and Scalable Codes", to appear in IEEE Transactions on Communications.

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Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Yakun Sun	0.25
Wiroonsak Santipach	0.50
Manish Agarwal	0.25
FTE Equivalent:	**1.00**
Total Number:	**3**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Michael L. Honig	0.10	No
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Koushik Sil

Total Number: 1

Names of personnel receiving PHDs

NAME
Yakun Sun
Wiroonsak Santipach

Total Number: 2

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

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Final Report
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1. Project Overview

An important property of high-performance wireless networks for military applications is *adaptability*. Namely, the transceiver nodes should measure and exploit properties of the channel and interference to optimize system objectives. This project has been concerned with joint transmitter-receiver adaptation in a distributed, peer-to-peer wireless network. System parameters that can be adapted at the transmitter include data rate, power, and signatures across space, time, and frequency.

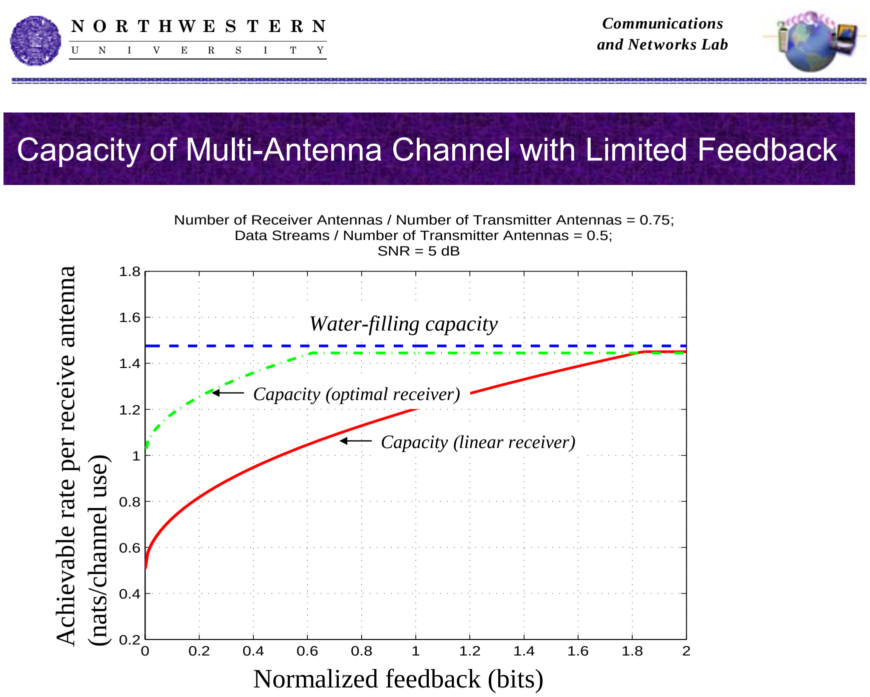
In what follows, we outline our main accomplishments. This work is aimed at increasing the spectral efficiency and reliability of wireless ad hoc networks. Our main focus has been on the design and performance of limited feedback schemes for relaying channel state information from a receiver to a transmitter. Knowledge of the channel at the transmitter can increase the achievable rate, and can greatly simplify the coding scheme. We also describe other related work on exchanging interference prices for distributed power control, evaluating the performance of multi-carrier Code-Division Multiple Access (CDMA) with interference suppression, and optimization of training overhead with least squares estimation (e.g., for adaptive interference suppression).

2. Multi-Antenna Performance with Limited Feedback

One way to boost the rate at which data can be reliably communicated across a single wireless link is to add antennas to the receiver and/or transmitter. While various space-time coding methods can exploit the presence of multiple transmitter antennas when the channel is not known at the transmitter, the channel capacity can be further increased if the transmitter knows the channel. Furthermore, knowledge of the channel at the transmitter can greatly simplify the coding scheme. That is, with a known channel the transmitter can signal along the eigen-modes of the channel, and optimally allocate power among these modes.

Providing channel information at the transmitter requires that the channel be measured at the receiver, and subsequently relayed to the transmitter over a feedback channel. In practice, the feedback rate, or number of bits that can be relayed to describe the channel, is limited. (This is due to limited feedback bandwidth, and because the channel and interference conditions may change.) We have studied the performance of multi-antenna links with *limited* feedback used to specify a linear "precoder" at the transmitter [1],[2]. The precoder is simply a matrix (the columns are "spatial signatures"), which attempts to align the transmitted signal along eigen-modes of the channel. *We have provided an upper bound on the data rate that can be reliably communicated as a function of the number of bits used to represent the precoding matrix.* This upper bound is illustrated in the following power point slide (taken from [2]), which shows achievable rate (capacity) as a function of feedback bits (normalized by the number of elements in the precoding matrix). The upper bound is obtained by using the B feedback bits to specify one of 2^B randomly selected precoding matrices.

The figure also compares the performance of an optimal (maximum-likelihood) receiver with a simpler linear receiver, both with limited feedback. These results show that given sufficient feedback (i.e., an additional bit per matrix element), the linear receiver can achieve the same performance as the much more complicated optimal receiver.

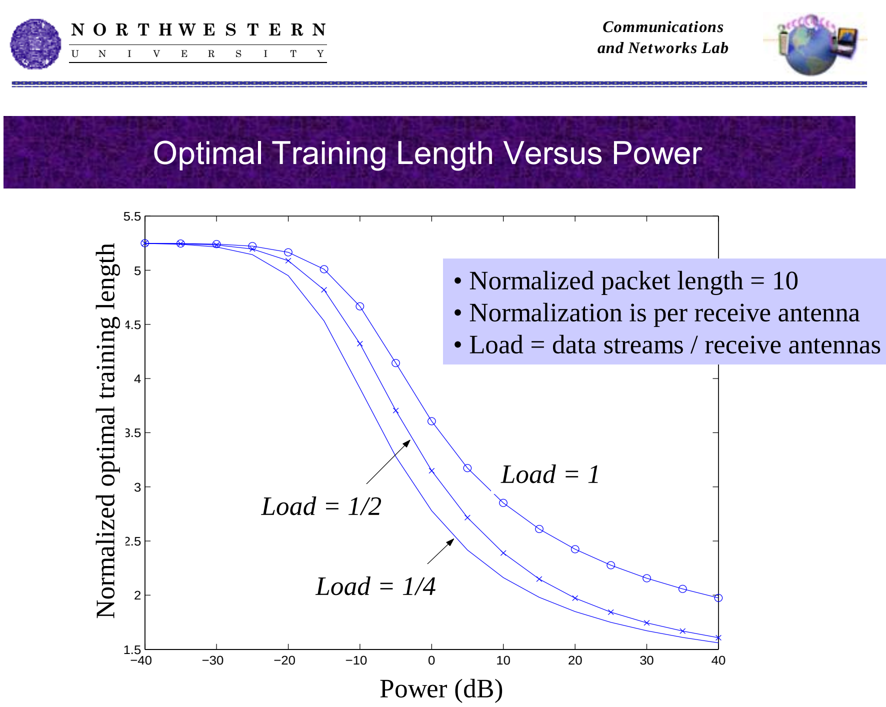


3. Optimization of Training Period for Interference Mitigation

In a packet-based wireless communications system, each packet typically contains a training sequence, which facilitates channel estimation, equalization, and interference mitigation at the receiver. Given a fixed packet size, the system performance (e.g., achievable rate) generally depends on the length of the training sequence. Namely, if the training sequence is too short, then the receiver cannot obtain a good estimate of the channel (or optimal equalizer filter). Conversely, if the training sequence is too long, then although the channel estimate may be accurate, not enough of the packet contains transmitted data. Hence there is an optimal training size, which can depend on the channel, signal-to-noise ratio (SNR), and packet length.

We have studied this problem for transmitters and receivers with multiple antennas and narrowband transmission (i.e., a flat fading multi-input/multi-output (MIMO) channel). The receiver is assumed to be linear, i.e., consists of a simple matrix filter that maximizes the received SNR for each transmitted data stream. The optimal matrix filter is typically estimated from the training sequence by minimizing a least squares cost criterion. (That is, it minimizes the sum squared errors between the transmitted symbols and filter outputs.) *We have been able to solve for the optimal training length explicitly when the system parameters (e.g., number of antennas and packet length) become large [3]. Furthermore, this "large system limit" accurately predicts the performance of relatively small systems. From this analysis we are able to show that the optimal training length increases as the square root of the packet size.* These results build upon our prior work, which characterizes the transient behavior of least squares estimators [4],[5].

This analysis is illustrated in the following power point slide, which shows the optimal training length, normalized by the number of receiver antennas, versus transmitted power. Curves are shown for different loads, or transmitted data streams per receive antenna. The normalized packet length (relative to number of antennas) in this example is 10. These results therefore show that at low power (SNR), about half the packet should be devoted to training, and as the power increases, the optimal training length decreases.



2. Limited Feedback and Training

We have studied the benefits of limited feedback for the following cases (i) the receiver knows the channel, and (ii) the receiver learns the channel via a training sequence. In both scenarios, we have considered a single-antenna, frequency-selective multi-carrier channel and a narrow-band MIMO channels (as previously discussed). With a multi-carrier channel, assumed to be known at the receiver, we have specified how much feedback is needed to achieve the optimal growth in capacity [6]. When the receiver learns the channel via a training sequence, an issue is how much power and how many symbols should be devoted to training. Assuming that the channel has a finite coherence time, increasing the amount of training improves the accuracy of the channel, but leaves fewer symbols for transmitting data symbols.

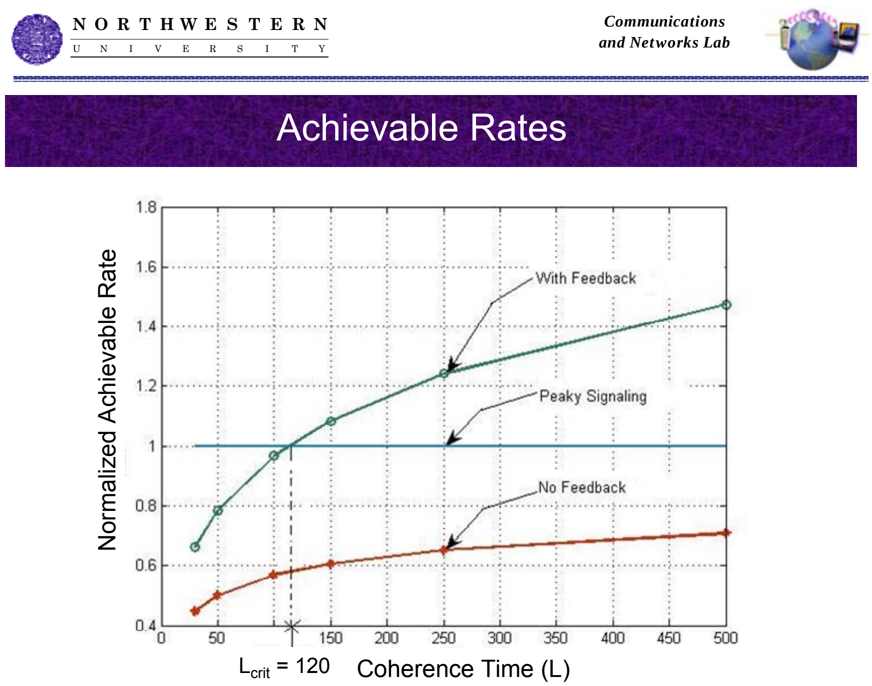
2.1 Multi-Carrier Signaling

Here we assume that the channel is divided into coherence bands (sub-channels) and coherence times. That is, within each coherence band the channel is assumed to be narrowband (flat) Rayleigh fading, and within each coherence time the channel is assumed to be constant (block fading). In this work, the sub-channel gains are assumed to be independent across frequency and coherence times. Motivated by ultra-wideband and spectrum sharing applications, we assume a large number of available sub-channels. Feedback is then used to indicate a subset of channels, which the transmitter uses for data transmission (i.e., a subset with large channel gains). Since the receiver does not know the sub-channel gains initially, we consider the following protocol:

1. During each coherence time, the transmitter chooses a subset of sub-channels to probe (i.e., transmit pilot symbols).
2. The receiver estimates the corresponding sub-channel gains and indicates to the transmitter which sub-channels have gains that exceed a predefined threshold.
3. The transmitter transmits data over the indicated sub-channels for the remainder of the coherence time.

The problem is then to determine how many channels to probe, the sub-channel gain threshold, the allocation of power and coherence time across pilot and data symbols, and the associated achievable rate.

The following power point slide, taken from [7], shows a plot of achievable rate versus coherence time (L) corresponding to optimized system parameters. Curves are shown corresponding to the feedback protocol just described, and the same protocol, but without feedback (i.e., the transmitter signals over all sub-channels probed). Also shown is the wideband channel capacity without feedback, which is achieved with “peaky” or “flash” signaling, i.e., the transmitted signal is impulsive in either time or frequency. In that case, the capacity depends only on the average received signal-to-noise ratio, and is independent of the coherence time. *With the preceding protocol, which relies on feedback, we show that the achievable rate increases as the log of the coherence time, and therefore exceeds the capacity with “flash” signaling when the coherence time exceeds a (positive) threshold value. This is because as the coherence time increases, the receiver is able to learn more sub-channel gains. Furthermore, we also show that the ratio of channels probed to the coherence time tends to zero with increasing coherence time, but slowly enough so that the channel estimation error for those sub-channels probed tends to zero.*



2.2 Beamforming

We have also considered limited training and feedback for Multi-Input/Single-Output (MISO) and MIMO links, in which the transmitter has multiple antennas, and the receiver has a single antenna. For the MISO channel, if the transmitter knows the channel, specified by the vector ***h***, then to maximize the achievable rate, the beamforming vector ***v*** should be matched to ***h***. We again assume that neither the receiver nor the transmitter knows the channel initially, and that the receiver learns the channel via a sequence of transmitted pilot symbols. The receiver then quantizes the beamforming vector and relays this to the transmitter. We again assume a block Rayleigh fading channel model. Each coherence block consists of a training period, i.e., transmitted pilot symbols, a feedback interval, in which the receiver relays the beamformer to the transmitter, and a data transmission interval. The problem is then to optimize the allocation of coherence time across training, feedback, and data transmission. Namely, the feedback should be matched to the quality of the channel estimate, i.e., there is no need to accurately quantize an inaccurate channel estimate, due to a short training period.

We assume that the receiver selects the transmit beamforming vector from a codebook containing 2^B random vectors, so that the feedback is limited to B bits. We have shown that this type of random vector quantizer is optimal in an asymptotic (large antenna) limit, and is observed to have essentially optimal performance for finite-size systems of interest [2,8].

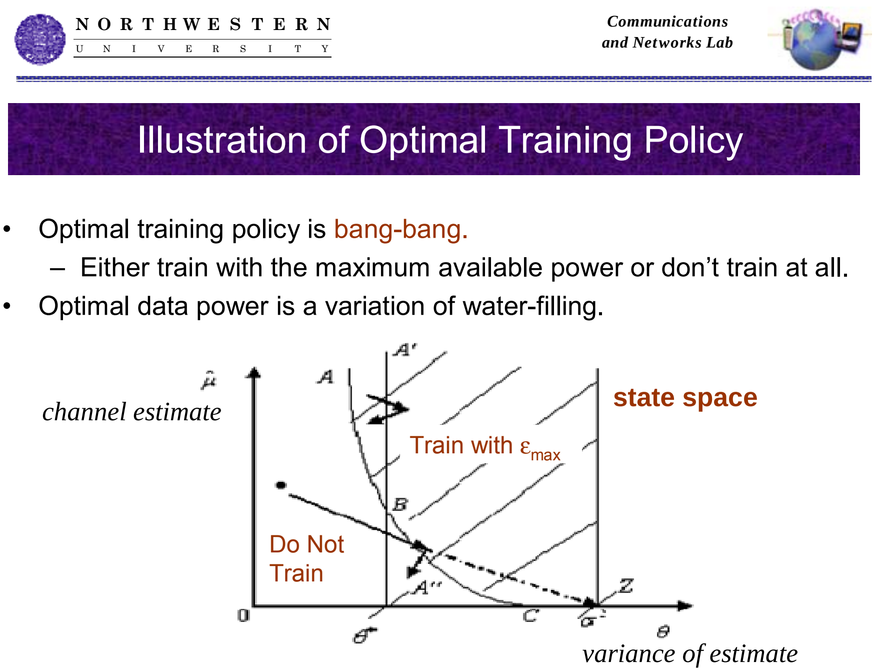
For this model we are able to compute the achievable rate versus coherence time [9]. As the coherence time increases, the rates converge, since both the receiver and transmitter obtain exact channel estimates. We have analyzed the achievable rate in the limit in which the coherence time L, number of transmit antennas N_t, and number of feedback bits

B become large with fixed ratios L/N_t and B/N_t. *This analysis shows that channel estimation error limits the number of transmit antennas that can be effectively used. Specifically, as N_t increases, activating on the order of $N_t/\log N_t$ transmit antennas maximizes the achievable rate. Also, the optimal feedback duration is asymptotically matched to the optimal training period.*

3. Adaptive Training

So far, the work described has assumed a block Rayleigh fading channel model in which the channel gains are independent across coherence blocks. In practice, it is more likely that the channel gains will be correlated across coherence blocks. In that case, at the beginning of each coherence block, the receiver has some *a priori* knowledge of the channel, which could be exploited to reduce the amount of training. That is, an accurate channel estimate from the preceding coherence block may obviate the need for additional training in the current coherence block. To gain insight into how training should be adapted with correlated fading, we have studied transmission through a block fading channel in which the channel gain changes according to a first-order Gauss-Markov process [10]. Pilot symbols are included in each coherence block, and the channel estimate is updated with a Kalman filter. Here we assume that the channel estimate (or features of the channel estimate) is fed back to the transmitter. Hence the estimate is used for coherent demodulation, and to adapt the allocation of power across data and pilot symbols.

For the preceding model, optimizing the data and pilot power, given the channel estimate, can be formulated as a dynamic program. To gain further insight, we have studied the limit in which the coherence time tends to zero, and the correlation between successive blocks tends to one, so that the channel process becomes a continuous-time Ornstein-Uhlenbeck process. *In this limit we have shown that the optimal pilot power control policy is "bang-bang", i.e., depending on the current system state (channel estimate and associated variance) the transmitter allocates either zero power, or the maximum available power to the pilot.* This is illustrated in the figure shown on the next power point slide. The region denotes the state-space, i.e., the *y*-axis is the estimated sub-channel mean, and the *x*-axis is the variance. (These are computed by the Kalman filter.) For a particular sequence of transmitted symbols, and channel and noise realizations, the optimal training policy and the Kalman filter produce a particular state trajectory. The optimal policy is represented by the boundary ABC shown in the figure. To the left of the boundary (corresponding to a smaller channel estimation variance), the pilot power is zero, and to the right of the boundary, the pilot power is the maximum available. *Numerical results have suggested that this optimal boundary is nearly vertical, indicating that the transmitter should train only when the variance of the channel estimate exceeds a threshold. Fortunately, this type of policy requires relatively little feedback.*



4. Distributed Power Control in Peer-to-Peer Networks

Power control for mitigating interference in a distributed, wireless peer-to-peer network can be significantly more difficult than in a cellular network. Namely, in the absence of centralized power assignments, users may experience severe interference (e.g., due to near-far effects), substantially degrading performance and capacity. While interference can be mitigated through physical layer techniques (e.g., multiple antennas), the performance of those techniques can be enhanced further through power control algorithms that account for interference to other nodes. This type of power control requires some information exchange among users, e.g., to indicate interference levels.

In [11], we have studied power control in a spread spectrum peer-to-peer network where all users spread their power over a single frequency band. We assume that each user is assigned a utility function, which indicates the value, or utility an individual user receives as a function of the received SINR. The utility function can account for different priorities, or fairness constraints. The system objective is then to coordinate user power levels to maximize the sum of the received utilities over all users.

We have proposed and analyzed an Asynchronous Distributed Pricing (ADP) algorithm, in which each user announces an "interference price", which is the marginal decrease in utility with respect to a marginal increase in received interference. The prices are then broadcast through the network, and used to determine an optimal power level for each user. We have shown that subject to certain (realistic) restrictions on the utility functions, this algorithm can achieve an optimal allocation of powers across users. (Note that if these "interference prices" were not exchanged among users, then to maximize utility, each user would simply transmit with maximum power. This can, of course, cause severe interference and loss in total utility.)

We have extended the ADP algorithm to multi-carrier (OFDM) types of systems [11], dynamic spectrum sharing scenarios [12], and have studied the performance of the ADP algorithm with limited information exchange among nodes in the network [13]. Our results show that the ADP algorithm provides a substantial performance gain, relative to no information exchange, and furthermore, this gain degrades gracefully as the radius of information exchange decreases.

4. Large System Analysis of Least Squares Interference Suppression

Large system analysis has been applied to CDMA and MIMO channels to predict the performance with random signatures (CDMA) and channel gains. The idea is to scale up the system parameters (e.g., users, processing, gain, number of transmit/receive antennas) keeping ratios fixed (e.g., in CDMA the load is users/processing gain). Explicit expressions for performance measures, such as Signal-to-Interference-Plus-Noise Ratio (SINR) can be obtained by applying results from the theory of large random matrices [14]. We have analyzed the performance of an adaptive receiver, which computes a least squares estimate of a linear interference suppression filter. This work builds upon our prior work [4], which applies to CDMA. More recently, we have extended this analysis to a more general class of random matrix channel models [5]. Performance evaluation of least squares estimation with random inputs is a classical, difficult problem, and these results appear to be the first, which give an exact characterization of performance versus sample size (amount of data used to compute the estimate). *In particular, we show that for a particular ratio of receive to transmit dimensions, all channels which have the same asymptotic SINR with an optimal (Minimum Mean Square Error) receiver, exhibit an identical transient response with least squares estimation.* As part of this work, we have developed a new technique for deriving the asymptotic eigenvalue distribution for a class of random matrices [15].

5. Source-Channel Coding

We have studied coding schemes for transmitting a Gaussian source through a block fading channel [16]. Assuming each block is decoded independently; the received distortion depends on the tradeoff between quantization accuracy and the probability of outage. Namely, higher quantization accuracy requires a higher channel code rate, which increases the probability of outage. We have evaluated the received mean distortion when either erasure coding or scalable (multi-resolution) coding is used to compensate for the fading. We have evaluated the mean received distortion in both cases, and have considered asymptotic limits in which the erasure code length tends to infinity, and the number of layers in the scalable code becomes large. *Our results show that erasure coding can provide less mean distortion than scalable coding, although scalable coding provides much less decoding delay.*

6. Technology Transfer

I have given seminars on the preceding topics at the Army Research Laboratory (ARL), Adelphi, MD, and have had further discussions on these topics with Drs. Brian Sadler and Ananthram Swami.

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